Investigate the Impact of Different Resource Allocation Strategies on the Design of Building Projects Using Simulation

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Summary

The design of building projects involves several types of resources such as architects, structural engineers, mechanical engineers, electrical engineers, and draftsmen, among others. For design firms to stay in business in this very competitive market, they need to manage their resources in a way that improves productivity and cost effectiveness. This task, however, is not simple and requires thorough analysis of process-level operations, resource use, and productivity. Typically, these operational aspects are the responsibility of the design office manager who assigns available resources to the different design projects to save time and lower design expenses. It is noted that limited studies have been carried out in the literature to model overall organizational operations and behavioral aspects, particularly in firms specialized in the design of building projects. In an effort to simplify the modeling process, a simplified modeling and simulation tool is used in this research. A simulation model representing an actual design office was developed assuming that the office performs designs for small, medium, and large size building projects. The developed model was used to simulate several alternatives and examine various resource assignment strategies. The simulation was conducted over ten years and the resulting productivity and income was measured.

1 Introduction

The construction industry has continuously been challenged by increasing project complexity and lack of resources. Design firms in particular have always been concerned about their competitiveness and existence in the current very competitive market. In many countries, competition is increasing and profit margins are narrowing. This high competition, coupled with the increasing project complexity, has forced many design firms to re-engineer their operations and work more productively with limited resources. Re-engineering, however, is not a one-size-fits-all concept (Hardy and Chaudhuri 1998). Rather, it requires thorough analysis of company-specific operations and resource use, which differ from one design firm to the other according to the nature of their business, size of projects, and the way they manage their resources.

Furthermore, recent unprecedented changes in technology have also forced many companies, including design firms, to optimize their operations and work more productively with limited resources. Efficient resource utilization for any firm, and design firms in particular, is neither simple nor straightforward due to the extensive interactions among the different work groups involved as well as the difficulties associated with resource assignment decisions. Typically, these operational aspects are the responsibility of the design office manager who assigns available resources to the different design projects so as to speed design development and lower the associated expenses. In doing so, the office manager may use different strategies for assigning resources to projects either individually or in teams of varying sizes. Each strategy may or may not suit the operational environment of a firm and, accordingly, different possibilities must be explored with both a process focus and a resource-use focus to optimize operations. Exploring the various options, therefore, requires the development of descriptive, analytical, and decision-making models, which accurately represent and simulate the office processes (Vanegas et al. 1993).

To optimize operations, managers need to explore different scenarios for carrying out project work under different conditions and constraints. One approach involves the development of analytical models, which accurately simulate the process being re-engineered, taking into consideration details such as task durations, resource quantity, and work capacity. In the engineering literature, however, limited studies have been carried out on modeling overall organizational operations and behavioral aspects, particularly in design firms. An exception is the work of Karaa et al. (Karaa et al. 1990) which used two operations management tools, line-of-balance and simulation modeling, to analyze the performance of different resource options for an engineering division of a public agency with repetitive operations. The study suggested practical solutions and outlined the advantage of modeling and simulation. More recently design of the team itself has been explored. Capitalizing on recent advances in computer technology and Artificial Intelligence (AI), a research team at Stanford University has developed a computational approach to model an engineering design team (Jin and Levitt 1996). They developed a computer software, "Virtual Design Team, VDT", which is a discrete-event simulation system that can predict the duration and direct cost of a certain design project. Similar to the earlier effort, the advantage of simulation was emphasized.

This research extends the concept, placing more focus on resource optimization in engineering organizations and design offices in particular. To enable the analysis of resource optimization needs, a simulation model of the operations in an actual design firm is developed. A number of experiments are then conducted in an attempt to organize operations, reduce operational costs, and improve the productivity of resources. The model, thus, becomes useful to project managers of Design/Build and Professional Construction Management Contracts in which project managers exercise control over the design and construction steps of projects. Comments on the model are made and potential applications of simulation in optimizing the resources in small-to-medium contractors are outlined.

2 Modeling and Simulation in Construction

Over the past two decades, several modeling and simulation systems have been introduced for the construction industry to support planning and production analysis. These tools include the commonly known CYCLONE system (Halpin 1973) and its improved versions, such as CIPROS (Tommelein and Odeh 1994). Until relatively recently, however, developing a simulation model has been too complex, too limited, or too costly (Paulson 1995 and Shi and AbouRizk 1997). These problems have contributed to the limited success of simulation in the construction industry. The process, traditionally, requires the user to be familiar with specific terminology and to be able to write proprietary computer code. This may not suit practitioners who are otherwise familiar with the details needed for accurate simulation. These difficulties have motivated several researchers to enhance the operational characteristics of available tools to become more automated and easy to use. Discussion of these efforts was included in Shi and AbouRizk (1997).

Recently, a new easy-to-use simulation software, “Process v4” (Process 2003), has been introduced commercially. The main advantages of this software are its simple flowchart-based modeling capabilities and its object-oriented simulation engine. Since the simulation accuracy of Process v4 has been found by the writer to be comparable to other construction tools (Zaneldin 2003), the software is used herein to develop the simulation model of the application at hand.

3 Modeling Design Office Operations

3.1 The Design Process

In a typical design firm, several design projects of varied sizes are usually processed in parallel. The design of each project goes through four main stages: 1) Conceptual design, 2) Preliminary design, 3) Detailed design; and 4) Final design. At the conceptual design stage, where the project scope is to be decided, client requirements, regulations, and site conditions are reviewed by an architect and different design concepts are generated. Feasible concepts are then presented to the client for a decision on the preferred alternative, thereby defining the project scope more clearly. The client's approval then signals the start of the preliminary design stage in which the selected alternative is revised and initial design is carried out by all involved disciplines (i.e., architectural, structural, mechanical and electrical). The main purpose in this stage is to select an appropriate design system for each discipline and provide an abstract framework for it. Once this is done, all disciplines start the detailed design stage to refine the various systems and to prepare detailed drawings and project specifications. Before the various designs are finalized, it is essential to conduct coordination meetings among the various disciplines. These meetings help to resolve conflicts, inconsistencies, and mismatches among the designs generated by the different disciplines. Afterwards, the final design stage commences and the design is refined further, based on the recommendations made at the coordination meetings.

3.2 Case Study Data

Based on the foregoing brief description of the design process for a typical design firm, three basic requirements become essential for building a model of the firm's operations: (1) a detailed breakdown of the tasks involved; (2) an estimate of the type, number, and hourly rates of the resources involved in each task; and (3) an estimate of the rate at which new design jobs are received by the firm. Data regarding these requirements are available within the design office and can be obtained through statistical analysis of past design projects. It is possible, for example, to determine the average number of small, medium, and large projects received annually by the design office and the rate by which they are received. Also, it is possible to determine average resource amounts used for various design tasks.

An actual design firm in the United Arab Emirates has been considered as a case study. The firm has its own staff for architectural, structural, electrical, and mechanical design in addition to other support staff such as draftsmen. After detailed analysis of several years of operation in the design office, a flowchart model of the firm's operation was compiled as shown in Fig. 2 (the notations used for the various elements of the model are described in Fig. 1). It is noted that Fig. 2 details three almost identical processes branching from node (1), which model small, medium, and large projects, separately. This is so as to differentiate between the three categories in terms of resources and work hours, as actually practiced in the design office being modeled. Figure 2 also shows the stages through which a design passes along its evolution path.

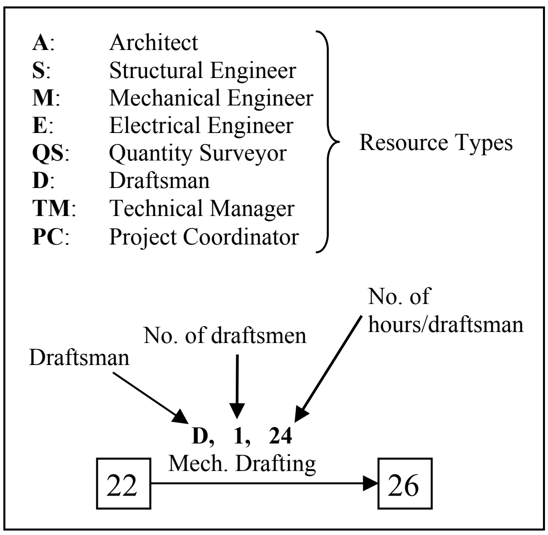

Fig. 1: Notations Used in the Design Process Model.

4 Developing a Simulation Model of a Typical Design Office

The first step to generate a simulation model for the design office operation was to draw a flowchart of the process (Fig. 2) using the drawing tools of the simulation software. Afterwards, the various resource categories (architects, structural engineers, mechanical engineers, electrical engineers, quantity surveyors, draftsmen, technical manager, and project coordinator) and their hourly rates were input to the resource sheet of the software. The number of each resource actually employed by the office was specified, and was later changed according to the simulation experiments conducted (described later). The activities and work-paths of the model were then configured as per the actual operation of the office. In general, work-paths were assigned appropriate resources, as stated above each work-path of Fig. 2. Also, input and output flow-objects were set to maintain the logical relationships of the model. The activities of the model were also configured with unlimited number of copies, meaning that more than one project can be processed simultaneously. To model the frequent arrival of new design projects (small, medium, or large), the start node of the flowchart was initially set to generate new flow-objects at short random intervals. The generated flow-objects were then routed to the small, the medium, or the large projects path, based on a probability of 50%, 30%, and 20%, respectively. This is to simulate the actual average percentages of small, medium, and large projects being received annually by the design office at hand. Accordingly, Node 1 was configured as a branching node with its path-routing option set to "probability". Also, since the work strategy of this design office was to assign the majority of resources to existing jobs, rather than new ones, the model was set up to reflect this strategy. Accordingly, in the model, the flowchart activities representing the final design stage were given higher priorities than the activities of the conceptual stage, in case they should compete for the same resource during the simulation. As a general rule in the model, the daily working period for all the resources was set to 8 hours per day, 5 days a week (Saturday to Wednesday). It was also considered that resources work 5 hours only each Thursday. Accordingly, the total work-hours per year = (8 X 5 + 5)/7 X 365 = 2346.43.

Once the simulation model was properly configured, the model was run continuous for a user-specified period of simulation time, starting from the first node. The Start node generates new flow-objects (according to the set rate of arrival of projects to the office) that are used with existing resources to meet the requirements of the start work-path. The Start work-path is then activated and, at the end of its activation, it generates the flow-object(s) required for its successor(s). The successor work-path(s) are then activated and the simulation process continues in the same manner, following the logic of the model. Whenever a work-path is activated, its start node (activity) counts the number of received flow-objects. Also, its end node counts the number of generated flow-objects. The object counts provide important information such as the number of completed designs at end of the simulation, the number of designs received, etc. This is in addition to important statistics related to total work hours of resources, idle times, and costs. These quantities become essential indicators of the overall performance of the design office and its resource utilization efficiency.

5 Management of the Design Process

Effective resource management is crucial to engineering firms in order to improve productivity, reduce cost, and stay successful. Due to the fluctuation in work volume, some design firms may engage in a process of hiring and layoffs, in addition to ad hoc resource assignments. To this end, the present simulation model can be used as an efficient tool that helps managers arrive at the optimum number of resource quantities and appropriate assignment strategy. Details of the various experiments conducted on the studied design office are described in the following subsections.

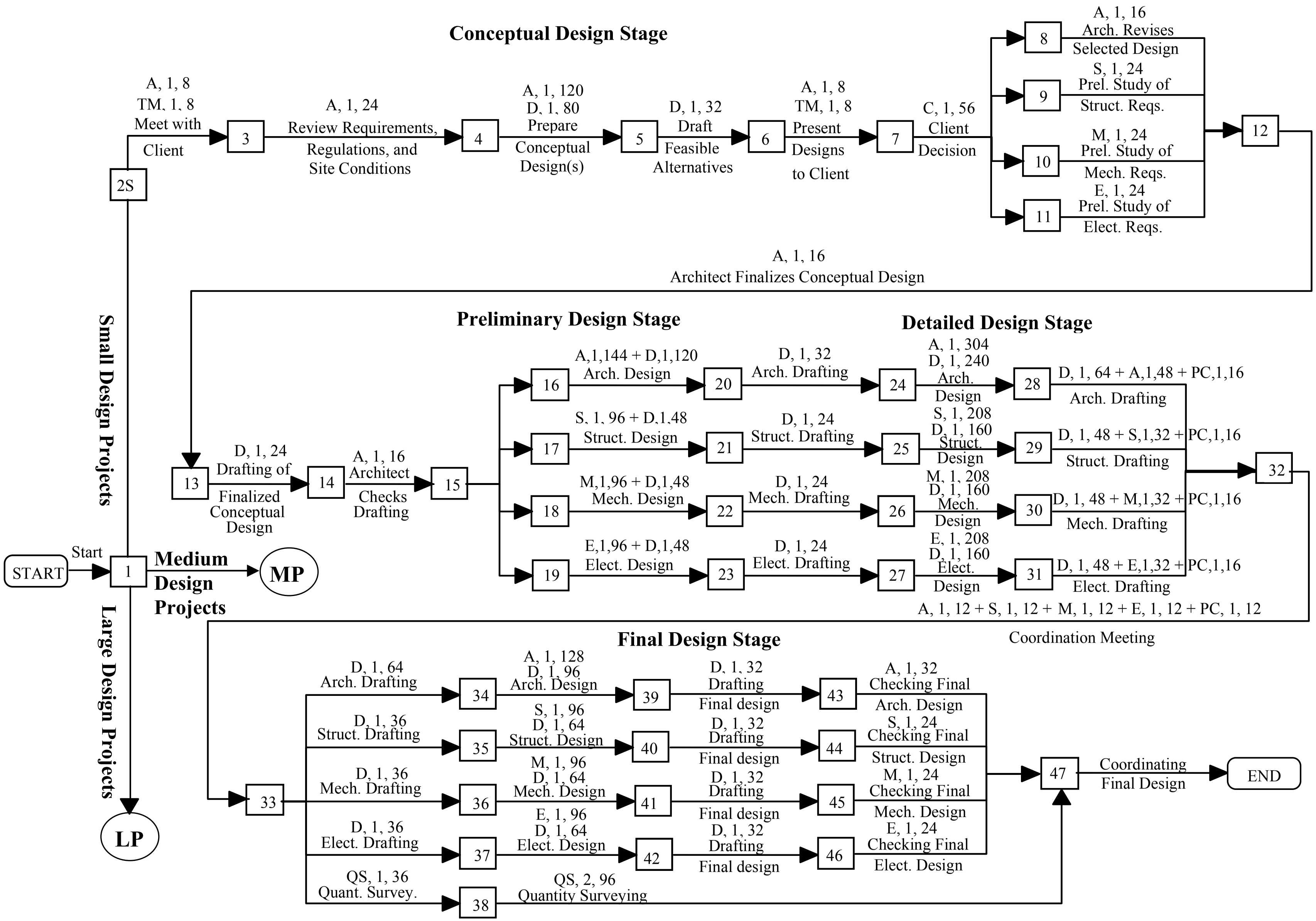

Fig. 2: The Design Process in a Typical Design Firm (Small Design Projects).

5.1 Resource Balancing

The developed simulation model proved useful for balancing resources. Different resource alternatives were modeled to arrive at the best combination of resources to finish the maximum number of projects per year, with an almost balanced workload among all types of resources. Several sequential experiments were conducted, each by modifying the number of architects, engineers of the various disciplines, and draftsmen and re-conducting the simulation. Initially, a combination of 5 architects, 4 structural engineers, 4 mechanical engineers, 4 electrical engineers, and 17 draftsmen was used. In addition, a fixed number of quantity surveyors (three), one project coordinator, and one technical manager were added. After filling the resource sheet of the software with these resources, the "start" node (Fig. 2) was set to generate new flow-objects (projects) at short intervals of 15 days. This was done to ensure that new projects were continuously entering the design office and that resources were not idle because of the lack of projects.

For each experiment, the model was run to simulate the office operation over a 10-year period. Accordingly, the simulation determined the number of small, medium, and large projects, which could be completed along with the effective hours spent by the various resources. A 10-year period was used to overcome the unrealistic start of the simulation when there were no on-going projects being designed by the office. The simulation results were then used to calculate the average number of projects completed per year and the average yearly number of hours spent by each resource, for different combinations of Architects, Engineers, and Draftsmen. A plot of the yearly work hours is shown in Fig. 3. The results of the first experiment (Fig. 3(a)) show that the yearly hours of each architect are much higher than those of all other resources, indicating higher work load. This fluctuation in the resource workload also suggests that the numbers of resources used in this alternative were not properly balanced. Another alternative was, therefore, created, increasing the number of architects to 7 and decreasing the number of draftsmen to 14, while keeping all other resources unchanged. With the additional Architects, the results of this experiment (Fig. 3(b)) show a reduction in the yearly work hours spent by architects even with more design projects being completed (54 small, 34 medium, and 31 large projects) as compared to the previous experiment (48 small, 29 medium, and 26 large projects). Also, the fewer draftsmen used in this experiment, added to the increase in completed jobs, resulted in an increase in the yearly work hours spent by draftsmen and engineers.

While the results of the second experiment exhibit a better resource balance (i.e., less fluctuation) than the first one, several other experiments were conducted in an attempt to balance the workload even further. The best results were obtained using 15 draftsmen and 8 architects in addition to the same number of other resources (Fig. 3(c)). Accordingly, these resources (15 draftsmen, 8 architects, and 4 engineers of each discipline) were considered as optimum for the design office being investigated and were fixed in further experimentation. It is noted that the level of the workload reached by the resources (e.g., 2205 hours/year for each draftsman, see Fig. 3(c)) is a reasonable workload and achieves an efficiency of 0.94 of a maximum work hours/year of 2346.43 (efficiency = 2205 / 2346.43 = 0.94). A summary of results for the experiments in Fig. 3 is shown in Table 1. Also, the total effort spent by the optimum set of resources, along with the total number of small, medium, and large projects completed in 10 years are shown in the screen capture of Fig. 4.

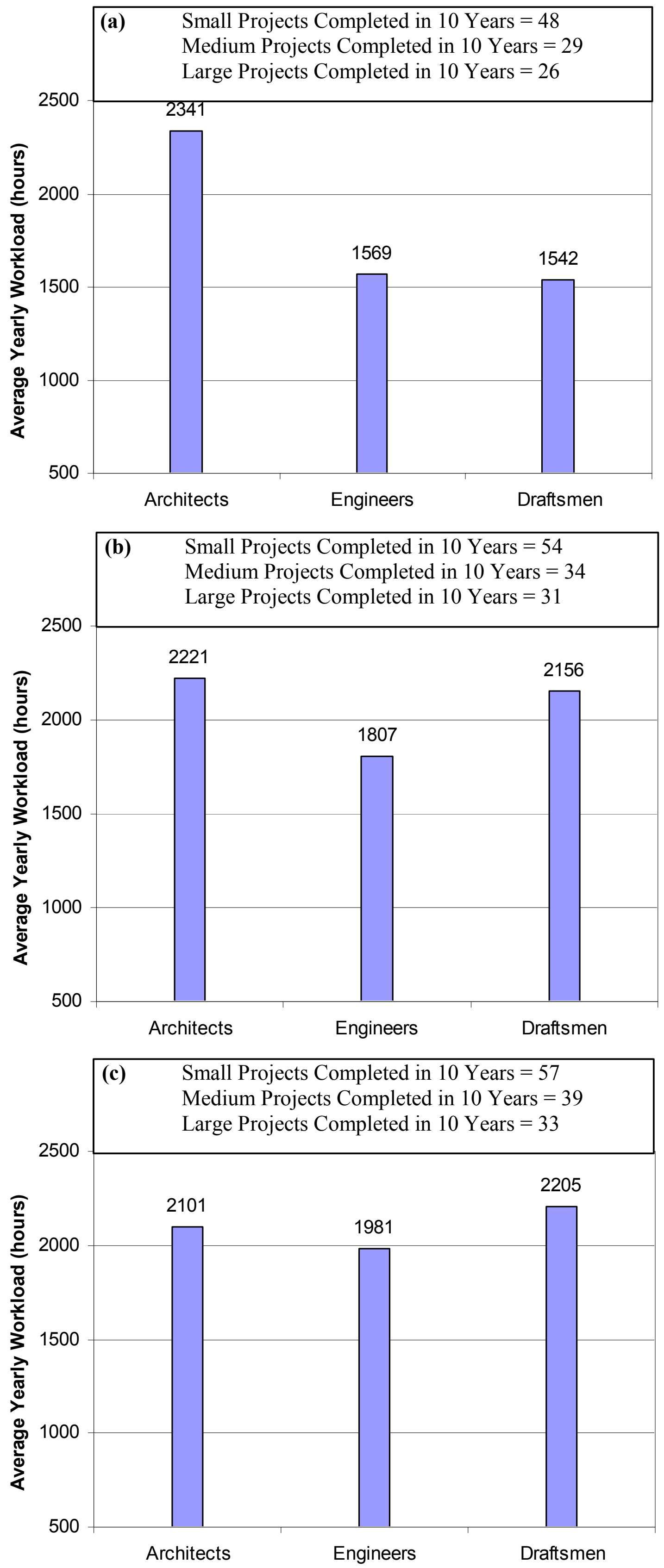

Fig. 3: Resource Workload with 4 Engineers of each Discipline and: (a) 17 Draftsmen and 5 Architects; (b) 14 Draftsmen and 7 Architects; and (c) 15 Draftsmen and 8 Architects.

Experiment	Resources*	Completed Designs			Yearly Work Hours		
		Small	Medium	Large	Architect	Engineer	Draftsman
1	5 A + 4 E + 17 D	48	29	26	2341	1569	1542
2	7 A + 4 E +14 D	54	34	31	2221	1807	2156
3	8 A + 4 E +15 D	57	39	33	2101	1981	2205

* A = Architect; E = Engineer (Structural, Electrical, and Mechanical); and D = Draftsman.

Table 1: Simulation Experiments for Resource Balancing (Simulation for a Period of 10 Years).

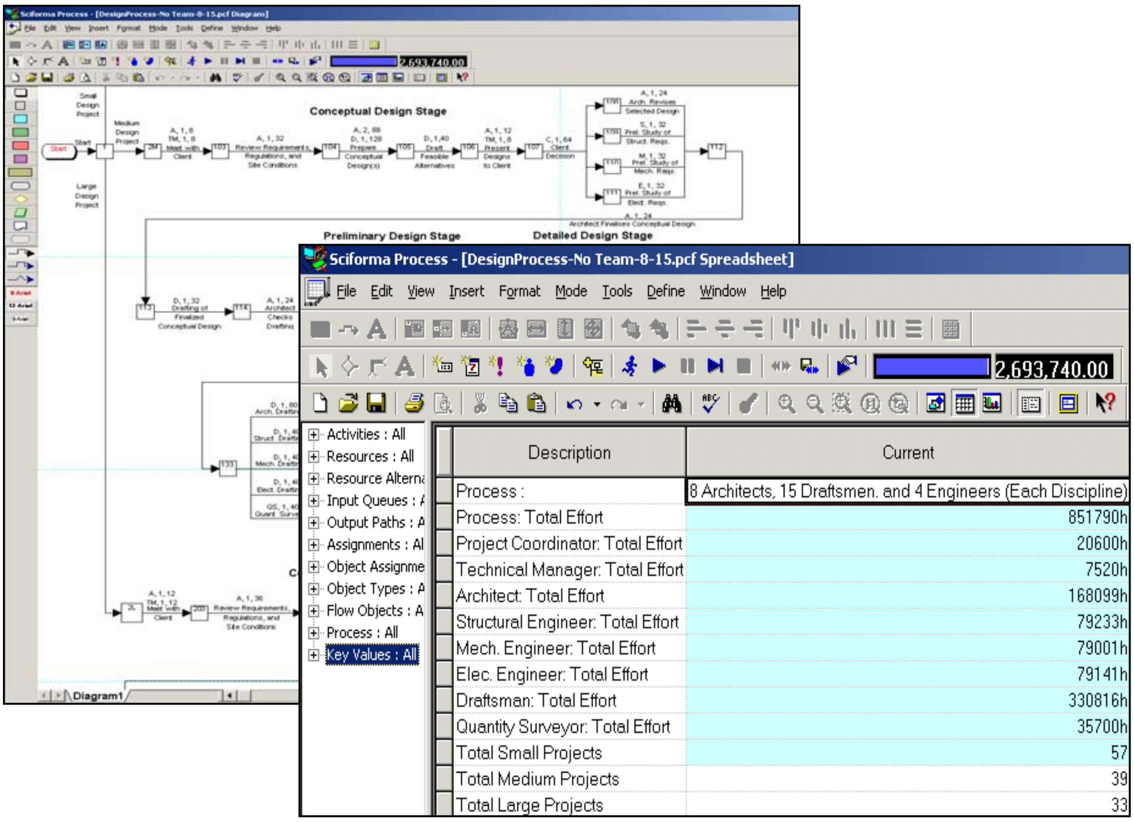

Fig. 4: Simulation Results Using 8 Architects, 4 Engineers from Each Discipline, and 15 Draftsmen.

6 Alternative Strategies of Assigning Resources

6.1 Teamwork vs. Individual Resource Allocation

During the design of any project, resources are assigned individually or as a team to different activities in the process. Traditionally, the strategy of assigning resources depends on the size of projects and the time frame available to complete such projects. To explore the differences between the strategies of teamwork versus individual assignment of resources, an experiment was conducted using the developed simulation model. The objective was to determine the best strategy for office managers to assign their resources to projects. The total numbers of resources available to the design office were fixed to be 8 architects, 15 draftsmen, 4 structural engineers, 4 mechanical engineers, 4 electrical engineers, 1 technical manager, 1 project coordinator, and 3 quantity surveyors, as determined from the previous experiment. In addition to an individual strategy involving no teamwork, seven alternative teamwork strategies were investigated, involving the assignment of teams to: 1) only small projects; 2) only medium projects; 3) only large projects; 4) both small and medium projects; 5) both small and large projects; 6) both medium and large projects; and 7) small, medium, and large projects. In these latter experiments, each resource type formed a team that was at most half of the total available, while the remaining worked as individual resources (e.g., the 4 structural engineers formed a structural team of 2 engineers, with 2 engineers working individually).

Seven variations of the model of Fig. 2 were generated for these experiments. For example, when the emphasis of the teamwork strategy was on small projects only (experiment 1), the part of the model dealing with small projects was changed so that each task was assigned a team, rather than an individual resource, without changing the total work hours. For example, the one architect resource needed for 144 hours in task 16-20 (Fig. 2) was changed to a team of 3 architects needed for 48 hours. Similarly, the revised models in the other six experiments were generated. The simulation was then run for a simulation period of ten years and the numbers of completed small, medium, and large projects in each experiment were determined and plotted as shown in Fig. 5. Also shown in Fig. 5 are results found for the model when there was no teamwork (first group of Fig. 5).

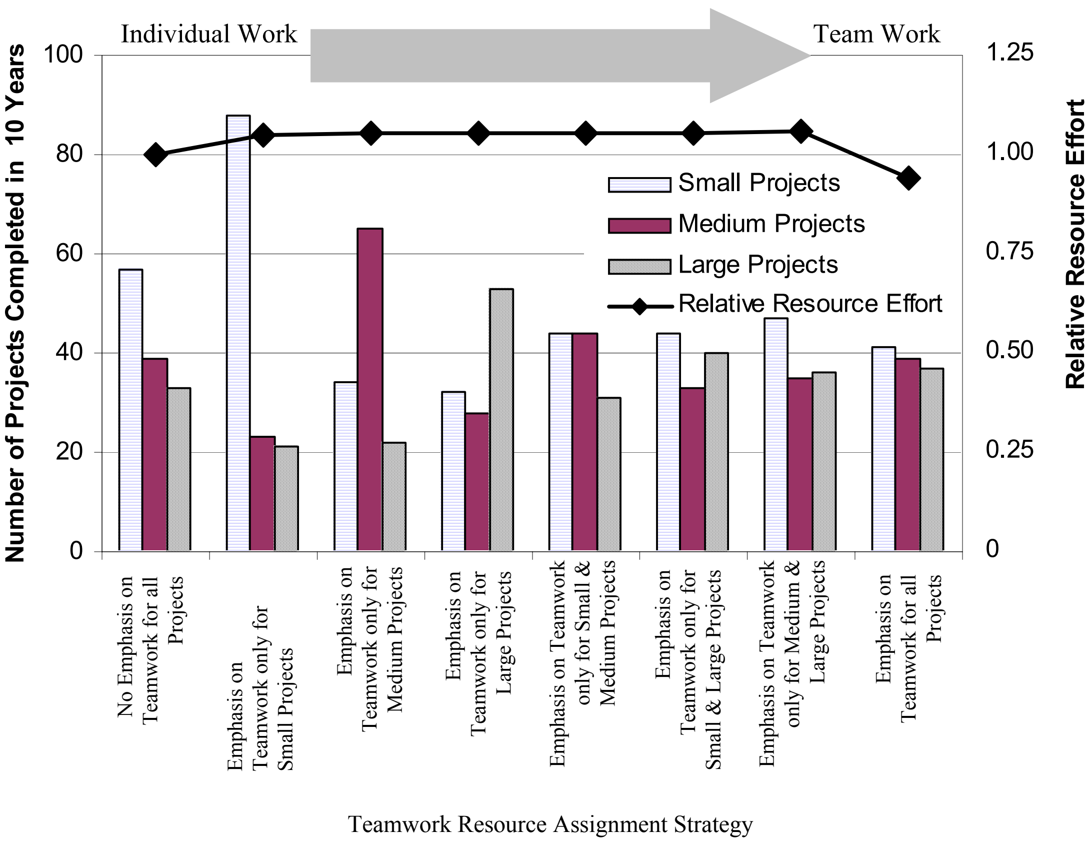

Fig. 5: Comparison among Different Teamwork Approaches.

The solid line plotted in Fig. 5 shows the ratio of the resource effort associated with the different teamwork strategies, relative to the resource effort for the case when there was no teamwork. It can be observed from the figure that, except in the case of assigning teams to all projects (small, medium, and large), the resource effort for all strategies is almost the same. When emphasis on teamwork is for all projects, the relative resource effort is equal to 0.94 (i.e., only 94 % of that required if there is no teamwork at all). The left-to-right relatively decreasing trend in the resource effort plot in Fig. 5 provides a quantitative measure of the benefits gained by using a teamwork strategy to assign resources, particularly for all projects. One obvious benefit is that the saved resources can be assigned to other tasks, such as supervision. To further differentiate between the different resource allocation strategies in terms of profitability to the design office, the volume of business achieved by the office for the different strategies was calculated. The volume of business was calculated using the information obtained from the different design firms assuming that small, medium, and large projects bring in design fees of 4%, 3%, and 2%, respectively, as a percentage of the total construction value of the project. Accordingly, the previously mentioned percentages represent design fees of $120,000, $450,000, and $1,000,000 for small, medium, and large projects, respectively. The results are plotted in Fig. 6 for the particular case when the total cost incurred by the design office for each of the eight assignment scenarios is considered to be the same over the ten-year period. (This was because the design office considered in this study was assumed to pay the salaries of all the resources over the ten-year period without any layoffs). From Fig. 6, the strategies of assigning teams to only large projects, only small and large, only medium and large, or all projects resulted in the highest volume of business, as compared to other strategies. One interesting observation here is that the highest volumes of business have resulted from assigning teams to large projects in the four strategies mentioned earlier.

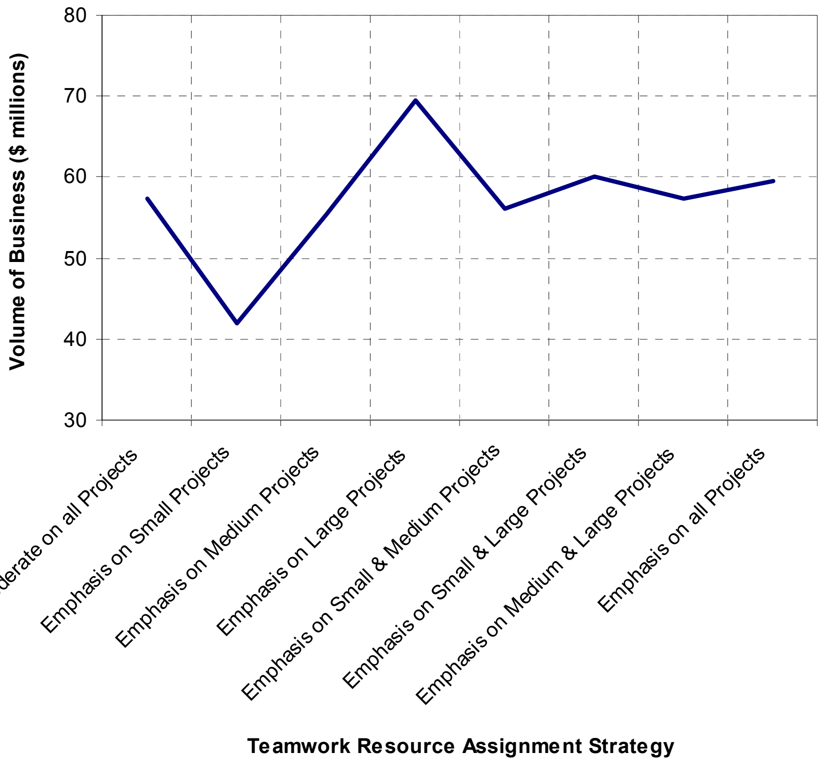

Fig. 6: Volume of Business Using Different Teamwork Approaches.

7 Recommendations and Future Extensions

In construction, simulation is a useful tool that can be used by project managers to model various construction activities that are of cyclic nature. Developing such models and providing automatic links between them and the project's schedule is one potential extension to this study, thereby refining cost estimates and determining realistic productivity figures. Although the numbers of used resources for the different design activities are done manually in this research, this process of resource allocation can be automated as a possible future extension to the present study.

The developments made in this research presented a novel application of simulation at the organizational level to optimize resources. The modeling of the operations within a design firm, as presented, can be of benefit to the project managers of design/build projects, particularly fast track projects, in addition to projects involving Professional Construction Management (PCM) contracts. The suggestion of alternative resource strategies to the individual organizations involved in a project can result in increased productivity and cost savings. Also, while the focus of this research is on design firms, the simulation model presented can be extended to model the operations of a contractor organization (bidding, execution, maintenance, etc), and thus can help in establishing effective resource strategies, particularly in multi-project environments. Similarly, possible extensions include the modeling of suppliers' and trade contractors' organizations.

Since the modeling process used in this study does not require background in simulation theory or programming skills, it is possible to use it for modeling and simulation of design activities of different types of design projects other than building projects. One very promising application is for the scheduling and resource management of maintenance operations in large infrastructure networks, such as highways, water, and sewer networks. With recent trends of privatizing these networks, demands on project managers with good resource management skills will increase and simulation can be a good potential tool in this regard.

8 Concluding Remarks

Prevailing market pressures have been forcing many design firms to optimize their operations and work more productively with limited resources. Overall optimization of office operations, however, is not a simple task and requires thorough analysis of the detailed work tasks and their resource use. It has been shown in this research that computer simulation is useful for analyzing office operations and investigating alternative management strategies. The presented simulation model can be used as a template that can be modified according to the particular environment of any design office. To this end, a flowchart-based simulation model of an actual design office in the United Arab Emirates was presented as a case study. Using the model, various simulation experiments were conducted to arrive at optimum resource quantities, workloads, and assignment strategies. Such results can be anticipated to increase the cost-effectiveness and timely operation of a design office, and consequently improve its overall productivity. In general, the developed model provides guidelines to help managers optimize their resource use and structure their re-engineering processes. These guidelines apply not only to design firms but also to contractors, suppliers and other organizations involved in the construction business.

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